Auditory and Vestibular Research

Contribution of Rapid Adaptation and Perceptual Learning Ability on Speech Perception in Noise in Elderly with Normal Hearing, Hearing Loss and Hearing Aid Use

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ABSTRACT

Background and Aim: The contributions of auditory and cognitive factors to speech perception in noise in the elderly are well studied; however, the roles of adaptive mechanisms, such as Rapid Adaptation (RA) and Perceptual Learning Ability (PLA), are less well explored. This study examined the relative contributions of RA, PLA, auditory processing and cognitive abilities towards speech perception in noise in the elderly.

Methods: Seventy-eight participants aged 60–75 years were divided into three groups: elderly with normal hearing (ENH), elderly with hearing impairment (EHI), and elderly with hearing aid (EHA). Auditory processing, cognitive abilities, and speech perception in noise were assessed. RA was quantified as the learning slope during exposure to time-compressed speech, and PLA was measured as retained improvement from pre- to post-training after a 2–4-day interval.

Results: Significant group differences were observed across auditory processing, cognitive measures, baseline speech perception, RA, and PLA. RA differentiated normal-hearing participants from hearing-impaired participants but did not differentiate between hearing-impaired participants. PLA emerged as the strongest predictor of speech perception in noise in the hearing-impaired groups, accounting for substantial variance beyond auditory and cognitive factors, whereas auditory measures predominated in the normal-hearing group.

Conclusion: RA and PLA make distinct contributions to speech perception in noise among elderly listeners. Adaptive mechanisms were not influenced by the hearing aid use, highlighting the need for rehabilitation approaches that incorporate targeted perceptual learning–based auditory training along with amplification.

Keywords: Adaptive learning mechanisms, rapid adaptation, perceptual learning ability, speech perception in noise.

Highlights

- Perceptual learning predicted speech-in-noise outcomes in elderly with hearing loss
- Rapid adaptation differed by hearing status, not by hearing aid use.
- Training-based rehabilitation may complement amplification in older adults.

Introduction

Speech perception is a complex auditory-cognitive process fundamental for decoding highly variable acoustic signals into meaningful linguistic units such as phonemes, syllables, and words [1]. This process relies on the dynamic interplay between sensory, cognitive, and linguistic systems, enabling individuals to extract consistent meaning from speech despite variations in speaker characteristics, background noise, or degraded signal quality [2]. Maintaining perceptual robustness is crucial for effective communication in real-world environments, which are seldom acoustically ideal.

However, the integrity of this perceptual mechanism can be substantially compromised in older adults and individuals with hearing impairment, leading to notable communication barriers [3]. These populations frequently report significant difficulties understanding speech in the presence of background noise, often described as "I can hear, but I cannot understand what was said"[4]. Such difficulties are further exacerbated in conditions involving rapid speech, particularly the fast-changing acoustic transitions within consonants [5].

Notably, speech-in-noise (SIN) perception difficulties can manifest even in older adults with normal audiometric thresholds, indicating that puretone audiograms alone cannot fully predict speech recognition performance in noise [6]. Consistent reports of poor speech perception in noise, even with hearing aids, highlight fundamental limitations of current rehabilitation strategies and suggest that simply restoring audibility is insufficient [7].

Beyond well-documented auditory and cognitive contributors, there has recently been a shift in focus to adaptive auditory mechanisms, specifically Rapid Adaptation (RA) and Perceptual Learning Ability (PLA) [8,9]. RA is characterised by swift, short-term improvements in performance following brief exposure to altered speech input, such as time-compressed or noise-vocoded speech [10]. In contrast, PLA encompasses more enduring, long-term modifications in the perceptual system emerging from sustained training, ultimately enhancing sensitivity to speech signals in complex acoustic environments [11].

Understanding these adaptive mechanisms is particularly important in degraded or rapidly changing acoustic signals, where adaptation is vital for successful comprehension [12,13]. Studies utilising time-compressed speech have revealed that models incorporating perceptual learning metrics offer more accurate predictions of speech recognition in noise than those that consider only auditory or cognitive variables [11,10,14].

While traditional models emphasize auditory and cognitive factors as primary sources of speech-in-noise deficits, recent research highlights the increasing importance of PLA and RA [14,15]. However, the comparative contributions of auditory processing deficits, cognitive impairments, RA, and PLA to speech perception difficulties remain poorly understood.

The present study addresses three critical gaps in the literature. First, while previous research has demonstrated that perceptual learning metrics improve predictive models of speech recognition [14], most studies have conflated rapid adaptation and longer-term perceptual learning [16,17]. We systematically distinguish between RA (immediate, session-based adaptation) and PLA (retained learning after consolidation). Second, we extend this framework to hearing aid users, a population for whom the impact of amplification on adaptive learning mechanisms remains poorly understood [18, 19]. Third, by comparing three distinct groups (elderly with normal hearing, untreated hearing loss, and hearing aid users), we isolate the specific contribution of adaptive mechanisms independent of audibility restoration. Hence, the present study aimed to examine the contributions of RA and PLA, along with auditory processing abilities and cognitive functions, on speech perception in noise in elderly individuals with normal hearing, those with untreated hearing loss, and hearing aid users.

Methods

Ethical Considerations

Written informed consent was obtained from all the participants. The study received ethical clearance from the Institutional Ethics Committee (JSSMC/IEC/07112024/34 NCT/PY/2024-25 Date: 08.11.2024).

Participants

A total of 78 participants (26 per group; age 60–75 years) were recruited to achieve 0.8 power at $\alpha = .05$, based on Rotman et al. [10]. Group 1 included elderly normal-hearing adults (ENH; Mean age 64.6) with thresholds ≤25 dB HL from 250–8000 Hz. Group 2 comprised elderly adults with mild–moderate sensorineural loss (EHI; Mean age 65.3; Puretone average = 26–55 dB HL at 500–4000 Hz). Group 3 included elderly regular hearing aid users (EHA; Mean age 63.2) who had been using bilateral digital hearing aids for a minimum of 2 years (range: 2-8 years; mean: 4.3 years, SD: 1.8 years). All participants used either behind-the-ear or receiver in the canal digital hearing aids with bilateral fittings. Hearing thresholds were similar to those of group 2 participants. All EHA participants used appropriately fitted digital hearing aids verified using real-ear measurements according to NAL-NL2 prescriptive targets.

Exclusion criteria were the presence of neurological and psychiatric problems, middle ear disorders, and chronic noise exposure. All participants were screened for cognitive function using the Montreal Cognitive Assessment (MoCA), a brief screening tool that assesses multiple cognitive domains, including attention, memory, language, visuospatial abilities, executive function, and orientation (score range: 0-30; scores ≥26 indicate normal cognition). The Screening for Central Auditory Processing (SCAP) was used to rule out significant central auditory processing disorders. SCAP is a validated screening tool that assesses auditory processing abilities, including gap detection, dichotic digits, and competing sentences (score range: 0-15, with scores >5 indicating potential CAPD). Participants with MoCA <26 or SCAP >5 were excluded to ensure that observed deficits were not primarily due to global cognitive impairment or diagnosed central auditory processing disorders

Tests Administered

All testing was completed across two sessions: the first included a baseline assessment followed by training, and the second included a post-training evaluation conducted 2–4 days later. The testing order was randomised, and adequate breaks were given to minimise fatigue.

Gap Detection Threshold

Temporal resolution was measured using a gap-detection task with broadband noise in Apex 3.0. A 3AFC 2-down, 1-up adaptive staircase procedure estimated the minimum detectable gap (ms). Gap Detection Threshold (GDT) was calculated as the mean of the last eight reversals, corresponding to 70.7% correct.

Temporal Fine Structure Sensitivity

The Temporal Fine Structure – Adaptive Frequency (TFS-AF) test developed by Fullgrabe et al. [20] was used. This test assessed sensitivity to interaural phase differences (IPD). Each trial contained two reference intervals (0° IPD) and one test interval with varying IPD. A 2-down, 1-up procedure determined the highest frequency at which IPD changes were detectable. Thresholds were the geometric mean of the last six reversals (Hz); lower values indicate better TFS sensitivity.

N-back Test

Working memory was measured using a 2-back task on the N-Back Evolution app. Participants viewed single-digit numbers and indicated whether each matched the previous number. Each session included a practice phase and three test trials; the highest score across trials was taken as the working memory score.

Selective Attention – Stroop Tasks

The Visual Stroop Task (Stroop Colour and Word Test) included Word Naming (baseline) and Colour Naming (interference). Colour words (RED, GREEN, BLUE) appeared in black or conflicting ink colours. Stimuli were presented via E-Prime, and responses were made using keys 1–3. After 12 practice and 36 test trials per condition, accuracy and reaction times were recorded. Interference scores (for ≥85% accuracy) were calculated by subtracting mean congruent from incongruent reaction times.

The Auditory Stroop Task used Kannada voice stimuli (“male,” “female,” “child”) spoken by male, female, or child voices, presented in congruent or incongruent conditions. Participants identified the speaker’s voice while ignoring the meaning of the words. Interference was calculated in the same way as the visual task.

Speech Perception in Noise

Two categories of Kannada sentences were used: Fifty Semantically Plausible and fifty Semantically Implausible (syntactically correct but nonsensical). Semantically implausible sentences were developed specifically for this study following established protocols for creating syntactically correct but semantically anomalous materials. Each implausible sentence maintained grammatical structure while violating semantic expectations. All sentences were validated by three native Kannada-speaking experts from speech and language sciences, who confirmed syntactic correctness and semantic implausibility. Sentences were matched to plausible counterparts for length (mean: 8.2 words, SD: 1.4), syllable count (mean: 12.6 syllables, SD: 2.1), phonetic complexity, and syntactic structure. A pilot study with 15 native Kannada speakers (not included in the main study) confirmed that implausible sentences were recognised as semantically anomalous while maintaining clear intelligibility. A female native Kannada speaker recorded all sentences in accordance with ANSI S3.1 (R2013). Two speech rates were generated: Natural Fast Speech (≈20% faster) and Time-Compressed Speech (40% compression via TD-PSOLA in PRAAT). Two maskers were prepared: Speech-

Shaped Noise (LTASS-matched) and Four-Talker Babble (filtered to LTASS). Sentences and noise were mixed at 0 dB and +3 dB SNR in MATLAB, RMS-normalised, and organised into ten balanced lists of ten sentences each.

Pre-Training Phase – Baseline Speech Perception

Baseline speech recognition in noise was assessed using 20 plausible and 20 implausible sentences presented at a natural fast rate in speech-shaped noise at 0 dB and +3 dB SNRs. Stimuli were delivered monaurally through a calibrated audiometer using Sennheiser HDA-200 headphones at each participant's PIPB maximum-score level. Sentence types and SNR conditions were randomised. Participants completed five practice trials with feedback to ensure understanding. Keyword scoring was used, and the percentage of correctly identified keywords was calculated.

Training Phase – Assessment of Rapid Adaptation

The participants were presented with 50 time-compressed sentences (25 plausible and 25 implausible) mixed with speech-shaped noise at both the SNRs, resulting in four training blocks (plausible 0 dB, plausible +3 dB, implausible 0 dB, implausible +3 dB). Within each block, sentences were presented sequentially, and participants repeated each sentence as accurately as possible. Keyword scoring was applied for each sentence response, allowing for trial-by-trial performance tracking. RA was operationally defined as the slope of the linear regression line fitted to the percentage of keywords correct across the 25 trials within each condition block. Steeper positive slopes indicated greater rapid adaptation. Separate RA slopes were calculated for each participant for each condition.

Post-Training Phase – Assessment of Perceptual Learning Ability

The post-training assessment was conducted 2–4 days after the training session to measure retention and consolidation of learning, distinguishing longer-term perceptual learning (PLA) from transient adaptation effects (RA). This delay period minimised the influence of short-term memory and immediate task familiarity while allowing sufficient time for consolidation processes.

Participants completed sentence recognition tasks (20 plausible and 20 implausible), presented at natural fast rate in speech-shaped noise at the same two SNRs. The procedure and scoring method were same as the pre-training phase. PLA was quantified as the improvement in recognition accuracy from pre-training to post-training, calculated as:

$$PLA\,(\%) = \left[\frac{(\text{Post training score} - \text{Pre training score})}{(100 - \text{Pre training score})}\right] x\ 100$$

This calculation accounts for ceiling effects by expressing improvement relative to the room for improvement available at baseline. Separate PLA scores were computed for each participant for each condition (plausible 0 dB, plausible +3 dB, implausible 0 dB, implausible +3 dB).

Statistical Analysis

Shapiro–Wilk tests indicated non-normal distributions ($p < .05$); therefore, non-parametric analyses were used. Group differences among ENH, EHI, and EHA participants were examined using Kruskal–Wallis ANOVA at $p = 0.05$. When significant overall group differences were found, follow-up pairwise comparisons were conducted using Mann–Whitney U tests with Bonferroni correction for three comparisons (adjusted $p = 0.016$) to control for Type 1 error. For regression analyses, statistical significance was determined at $p = 0.05$. Hierarchical regression analyses were conducted to identify predictors of speech perception in noise. For each group, separate models were run for plausible and implausible sentences at both SNRs. The model included peripheral hearing measures (pure-tone average, speech recognition threshold, and speech identification scores) in the first block, followed by cognitive measures (N-back scores, visual and auditory Stroop interference), auditory processing measures (GDT, TFS-AF, and SCAP), perceptual learning ability (PLA), and rapid adaptation slopes in subsequent blocks.

Results

Table 1 presents the median and interquartile ranges for auditory processing, cognitive measures, baseline speech perception in noise, rapid adaptation, and perceptual learning ability across groups. The results of statistical analysis of group comparisons for all the measures are provided in Table 2.

Auditory Processing Abilities

For GDT, there were significant overall group differences, and significant differences were observed across all paired comparisons ($p < 0.05$). The TFS-AF results also indicated significant group differences. Post hoc analyses showed differences only between ENH and EHI and EHA groups, but not between EHI and EHA groups (p > 0.05).

Cognitive Measures

There were significant overall group differences on measures N-back testing and auditory stroop interference measures. Post hoc results were significant for all paired comparisons (p < 0.05) for these two measures. However, there were no significant differences between the groups on measures of visual stroop interference.

Baseline Speech Perception in Noise Performance

Significant overall group differences were noted for both semantically plausible and implausible sentences in both the SNRs (p < 0.001). Even post hoc results showed significant pairwise comparisons, except between ENH and EHA for perception of semantically plausible sentences at +3 dBSNR.

Rapid Adaptation

There were significant overall group differences in all the conditions and SNRs, except for plausible sentences at +3 dBSNR. Post-hoc results showed significant pairwise differences only between the normal-hearing and hearing-loss groups. There was no significant difference between the two hearing loss groups.

Perceptual Learning Ability

There were significant overall differences between the groups in all conditions except at +3 dBSNR for implausible sentences. For both SNRs in semantically plausible conditions, post hoc analyses showed significant differences across all pairwise comparisons, except between ENH and EHA participants. The PLA for implausible sentences at 0 dBSNR showed significant differences only in the hearing-impaired groups.

Predictors of Speech Perception in Noise

The results of the hierarchical regression analysis for the three groups are presented separately in Tables 3, 4, and 5. In the ENH group, for plausible sentences at 0 dBSNR, speech identification score was the only significant predictor. For implausible sentences at 0 dBSNR, puretone average emerged as a consistent predictor across several models, including the final Model 5. No significant statistical improvements were observed at +3 dB for either plausible or implausible sentences.

In the EHI group, for plausible sentences at 0 dBSNR, PLA produced a large increase in variance explained (Model 4), with PLA showing a strong predictive effect. The +3 dBSNR condition also yielded significant improvements, with the final model (Model 5). Significant predictors included speech recognition threshold, speech identification score, Visual Stroop interference, PLA improvement, and RA slope. For implausible sentences, PLA and MoCA scores were significant contributors at 0 and +3 dBSNRs, respectively, with MoCA predicting the perception at +3 dBSNR.

In the EHA group, for plausible sentences at both SNRs, no model step produced a statistically significant improvements. For implausible sentences at 0 dB SNR, PLA again contributed substantially, accounting for a substantial proportion of the variance. This effect remained significant in the final model also. No substantial improvement in variance was observed in the +3 dB implausible condition.

Discussion

The present study demonstrates that different variables differentially influence speech perception in noise across elderly populations, with distinct patterns emerging for elderly individuals with normal hearing (ENH), hearing impairment (EHI), and hearing aid users (EHA). Most notably, PLA emerged as the dominant predictor among hearing-impaired individuals, while auditory and cognitive factors played a more prominent role among normal-hearing elderly adults, highlighting the complex interplay between adaptive mechanisms and traditional audiological factors.

Auditory processing abilities revealed differential patterns across groups, with GDT distinguishing all three populations, consistent with previous findings demonstrating progressive temporal processing deficits in ageing and hearing loss [21,22]. However, TFS-AF only differentiated ENH from both hearing loss groups (EHI and EHA), suggesting that hearing aids do not restore fine temporal processing abilities [23].

The cognitive measures revealed similar patterns, with N-back working memory and auditory Stroop interference tasks differentiating all groups, while visual Stroop interference showed no differences [24]. This selective impairment in auditory-specific cognitive processing supports the Framework for Understanding Effortful Listening, which emphasizes the increased cognitive load associated with degraded auditory input [18]. This pattern may be influenced by several factors, including the duration and severity of auditory deprivation, which has been shown to affect auditory-specific cognitive processing through cross-modal reorganisation. While we did not systematically measure the duration of hearing loss (only the duration of hearing aid use in the EHA group), future research should examine whether longer periods of auditory deprivation produce more pronounced modality-specific cognitive changes, which may explain the preserved visual processing observed here.

The RA abilities demonstrated a clear dichotomy between normal-hearing and hearing-impaired populations, with no significant differences between EHI and EHA groups. This finding suggests that hearing aids, while providing amplification, do not restore the neural mechanisms underlying rapid perceptual adaptation [25,26]. The inability of hearing aids to normalize rapid adaptation may explain persistent speech-perception difficulties in noise despite adequate audibility [26]. The similar RA performance between EHI and EHA groups indicates that current hearing aid technology fails to address these fundamental adaptive deficits, potentially explaining why many users continue to experience communication difficulties in challenging acoustic environments [27]. Alternatively, the similar RA performance between the EHI and EHA groups may reflect the limited sensitivity of the RA measure in differentiating between treated and untreated hearing loss when the underlying sensory deficit persists. The RA task may have insufficient resolution to detect the subtle improvements in adaptive capacity that hearing aids might provide, or ceiling/floor effects in the time-compressed speech paradigm may have masked group differences. Regardless of interpretation, the current findings indicate that addressing adaptive learning deficits requires approaches beyond traditional amplification alone.

Perceptual learning ability emerged as the most striking differentiator across groups and the strongest predictor of speech perception performance. In the EHI group, PLA accounted for 59.5% of the variance in speech perception, demonstrating its critical importance when sensory input is compromised [28]. This contrasts sharply with ENH individuals, where audibility measures dominated predictions, and EHA users, where PLA was significant only for implausible sentences. These findings align with theoretical frameworks suggesting that perceptual learning becomes increasingly crucial as signal degradation increases [8], i.e., hearing-impaired individuals have greater reliance on adaptive plasticity mechanisms [26]. Furthermore, the reduced PLA influence in hearing aid users compared to unaided hearing-impaired individuals suggests that amplification may alter, but not necessarily improve, perceptual learning dynamics [12]. This finding has profound implications for understanding why some individuals benefit more from hearing aids than others, potentially relating to individual differences in perceptual learning capacity [11].

Our findings reveal distinct clinical utilities for RA and PLA measures. RA successfully differentiated hearing status (normal hearing vs. hearing loss) but failed to distinguish between treated (EHA) and untreated (EHI) hearing loss. In contrast, PLA showed differential patterns across all three groups. Specifically, for semantically plausible sentences, PLA distinguished ENH from EHI and EHI from EHA, suggesting partial restoration of learning capacity with amplification. The PLA also accounted for 59.5% of the variance in the EHI group but only 42.6% in the EHA group for challenging conditions, indicating that hearing aid use modifies the relative contribution of adaptive learning to speech perception outcomes. These patterns suggest that PLA is a more sensitive and clinically informative measure for predicting speech perception abilities in hearing aid users. Furthermore, PLA can be used to assess rehabilitation outcomes and to identify individuals who may benefit from supplementary perceptual learning training. RA, while theoretically important, may have limited utility as a clinical outcome measure given its binary pattern of differentiation and potential limitations in measurement sensitivity.

These findings have significant clinical implications for audiological rehabilitation. Current approaches primarily focus on restoring audibility through amplification while neglecting adaptive plasticity mechanisms crucial for speech understanding [4]. The prominence of PLA in predicting speech perception success suggests that rehabilitation programs should incorporate auditory training protocols specifically targeting perceptual learning abilities. Furthermore, differential contribution patterns across groups indicate that one-size-fits-all approaches are inadequate; instead, interventions should be tailored to individual profiles of auditory, cognitive, and adaptive abilities.

Several limitations required further consideration. The cross-sectional design prevents examination of longitudinal changes in PLA with hearing aid experience. Additionally, the specific stimulus materials and testing conditions may not fully represent real-world listening challenges. Future research should investigate longitudinal changes in PLA following hearing aid fitting, examine whether PLA assessment can predict hearing aid success, and explore training paradigms designed to enhance perceptual learning abilities.

Conclusion

This study demonstrates that rapid adaptation and perceptual learning ability play critical and distinct roles in speech perception in noise among elderly listeners. The differential contributions of variables across elderly populations, particularly the prominence of PLA in hearing-impaired individuals. Whereas, normal-hearing older adults relied primarily on auditory and cognitive factors. Hearing aid use did not restore either the adaptive mechanisms or temporal processing abilities, highlighting limitations of amplification alone. These findings emphasise the need for rehabilitation approaches that integrate targeted auditory training based on individual auditory, cognitive, and learning profiles, which may substantially improve communication outcomes.

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Conflict of interest: There is no conflict of interest to disclose

Informed consent: Informed consent was obtained prior to the evaluation, following a briefing about the study for all participants.

Compliance with Ethical Standards: According to the 1964 Helsinki declaration, the research complies with ethical standards. The research was approved by JSS Institutional Ethics Committee (JSSMC/IEC/07112024/34 NCT/PY/2024-25 Date: 08.11.2024).

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Author Contributions:

VK: Study design, interpretation of results, statistical analysis, drafting the manuscript.

ILK: Acquisition of data and preparation of the initial draft.

SSS: Supervision and critical revision of the manuscript.

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Table 1.
Descriptive statistics of auditory processing, cognitive measures, baseline speech perception in noise, rapid adaptation, and perceptual learning ability across groups

Measure / Condition	**Elderly Normal Hearing Median (IQR)**	**Elderly Hearing Impaired Median (IQR)**	**Elderly Hearing Aid Users Median (IQR)**
Auditory processing			
Gap Detection Thresholds (in milliseconds)	12.33 (6.33)	14.96 (15.52)	15.54 (18.22)
Temporal Fine Structure – Adaptive Frequency (in hertz)	884.43 (340.19)	792.54 (510.65)	612.50 (340.32)
Cognitive measures			
Working Memory – N-back Test	6.50 (4.00)	4.00 (5.00)	6.00 (5.00)
Visual Stroop Interference	153.10 (514.60)	178.74 (281.02)	110.05 (242.33)
Auditory Stroop Interference	197.85 (394.70)	143.26 (295.97)	53.26 (259.99)
Baseline speech perception in noise (in percentage)			
Plausible sentences, +3 dB SNR	45.63 (15.80)	35.32 (9.71)	42.91 (6.82)
Plausible sentences, 0 dB SNR	40.20 (18.41)	29.82 (8.42)	38.64 (13.84)
Implausible sentences, +3 dB SNR	38.55 (8.80)	24.35 (11.50)	33.50 (7.54)
Implausible sentences, 0 dB SNR	33.35 (13.23)	21.60 (11.70)	25.80 (8.50)
Rapid adaptation (slope)			
Plausible sentences, +3 dB SNR	0.25 (0.58)	0.31 (0.29)	0.39 (0.28)
Plausible sentences, 0 dB SNR	0.16 (0.67)	0.37 (0.52)	0.41 (0.51)
Implausible sentences, +3 dB SNR	0.16 (0.92)	0.33 (0.27)	0.34 (0.21)
Implausible sentences, 0 dB SNR	0.29 (0.83)	0.41 (0.48)	0.43 (0.33)
Perceptual learning ability (post training improvement in percentage)			
Plausible sentences, +3 dB SNR	9.38 (2.75)	6.57 (7.91)	11.15 (3.35)
Plausible sentences, 0 dB SNR	13.00 (4.75)	4.50 (4.50)	12.48 (5.45)
Implausible sentences, +3 dB SNR	3.75 (2.28)	3.35 (5.00)	5.35 (4.75)
Implausible sentences, 0 dB SNR	3.00 (2.75)	4.85 (2.75)	4.80 (3.75)

Note: IQR = Inter Quartile Range; SNR = signal-to-noise ratio.

Table 2.
Results of statistical analysis of auditory processing, cognitive measures, baseline speech perception in noise, rapid adaptation, and perceptual learning ability across groups

Measure / Condition	**Kruskal-Wallis (χ^2)**	**p-value**	**Post-hoc comparisons (Mann-Whitney U)**
Auditory processing			
Gap Detection Thresholds	27.392	< 0.001	ENH vs EHI: U = 99.00, p = 0.006 ENH vs EHA: U = 22.00, p < 0.001 EHI vs EHA: U = 80.00, p < 0.001
Temporal Fine Structure – Adaptive Frequency	26.457	< 0.001	ENH vs EHI: U = 50.500, p < 0.001 ENH vs EHA: U = 30.000, p < 0.001 EHI vs EHA: U = 147.00, p = 0.151
Cognitive measures			

Measure / Condition	**Kruskal-Wallis (χ^2)**	**p-value**	**Post-hoc comparisons (Mann-Whitney U)**
Working Memory – N-back Test	18.963	< 0.001	ENH vs EHI: U = 43.500, p < 0.001 ENH vs EHA: U = 103.000, p = 0.007 EHI vs EHA: U = 143.500, p = 0.015
Visual Stroop Interference	4.964	> 0.001	Not significant
Auditory Stroop Interference	18.772	< 0.001	ENH vs EHI: U = 126.00, p = 0.045 ENH vs EHA: U = 56.00, p < 0.001 EHI vs EHA: U = 88.00, p = 0.002
Baseline speech perception in noise			
Plausible sentences, +3 dB SNR	40.067	< 0.001	ENH vs EHI: U = 0.000, p < 0.001 EHI vs EHA: U = 0.000, p < 0.001 ENH vs EHA: U = 187.000, p = 0.719
Plausible sentences, 0 dB SNR	39.874	< 0.001	ENH vs EHI: U = 0.000, p < 0.001 EHI vs EHA: U = 0.000, p < 0.001 ENH vs EHA: U = 76.000, p = 0.003
Implausible sentences, +3 dB SNR	39.620	< 0.001	ENH vs EHI: U = 0.000, p < 0.001 EHI vs EHA: U = 0.000, p < 0.001 ENH vs EHA: U = 23.000, p = 0.006
Implausible sentences, 0 dB SNR	39.220	< 0.001	ENH vs EHI: U = 2.000, p < 0.001 EHI vs EHA: U = 13.000, p < 0.001 ENH vs EHA: U = 34.000, p = 0.008
Rapid adaptation			
Plausible sentences, +3 dB SNR	2.735	> 0.001	Not significant
Plausible sentences, 0 dB SNR	27.801	< 0.001	ENH vs EHI: U = 48.500, p < 0.001 ENH vs EHA: U = 25.000, p < 0.001 EHI vs EHA: U = 157.500, p = 0.238
Implausible sentences, +3 dB SNR	17.234	< 0.001	ENH vs EHI: U = 68.500, p < 0.001 ENH vs EHA: U = 72.000, p <

Measure / Condition	Kruskal-Wallis (χ^2)	p-value	Post-hoc comparisons (Mann-Whitney U)
			0.001 EHI vs EHA: U = 196.000, p = 0.910
Implausible sentences, 0 dB SNR	10.840	< 0.001	ENH vs EHI: U = 96.500, p = 0.005 ENH vs EHA: U = 95.500, p = 0.004 EHI vs EHA: U = 199.000, p = 0.978
Perceptual learning ability			
Plausible sentences, +3 dB SNR	37.745	< 0.001	ENH vs EHI: U = 6.000, p < 0.001 EHA vs EHI: U = 4.000, p < 0.001 ENH vs EHA: U = 196.000, p = 0.910
Plausible sentences, 0 dB SNR	36.247	< 0.001	ENH vs EHI: U = 9.500, p < 0.001 EHA vs EHI: U = 10.500, p < 0.001 ENH vs EHA: U = 159.500, p = 0.270
Implausible sentences, +3 dB SNR	1.108	> 0.001	Not significant
Implausible sentences, 0 dB SNR	6.978	< 0.001	ENH vs EHI: U = 129.000, p = 0.053 ENH vs EHA: U = 166.500, p = 0.359 EHA vs EHI: U = 111.500, p = 0.016

Note: ENH = elderly with normal hearing; EHI = elderly with hearing impairment; EHA = elderly hearing aid users; SNR = signal-to-noise ratio. Post hoc comparisons are reported using Mann-Whitney U tests. "Not significant" indicates no significant pairwise differences reported.

Table 3.
Results of Hierarchical Regression Analysis for the Elderly Normal Hearing (ENH) Group

Condition	Model	R^2	Adj. R^2	F	p	ΔR^2
Plausible +3 dB SNR	1	0.099	-0.070	0.59	0.633	—
	2	0.449	0.127	1.39	0.292	0.350
	3	0.573	0.099	1.21	0.392	0.125
	4	0.574	-0.011	0.98	0.525	0.001
	5	0.578	-0.146	0.80	0.651	0.003
Plausible 0 dB SNR	1	0.285	0.151	2.12	0.137	—
	2	0.536	0.266	1.98	0.142	0.251
	3	0.621	0.200	1.47	0.286	0.085
	4	0.732	0.363	1.98	0.170	0.111
	5	0.742	0.299	1.68	0.252	0.010
Implausible +3 dB SNR	1	0.119	-0.047	0.72	0.556	—
	2	0.345	-0.037	0.90	0.535	0.226

	3	0.382	-0.304	0.56	0.813	0.037
	4	0.617	0.090	1.17	0.422	0.235
	5	0.618	-0.037	0.94	0.558	0.001
Implausible 0 dB SNR	1	0.356	0.235	2.95	0.064	—
	2	0.534	0.261	1.96	0.146	0.177
	3	0.666	0.295	1.79	0.196	0.132
	4	0.683	0.246	1.56	0.269	0.017
	5	0.753	0.330	1.78	0.227	0.071

Model 1 – Peripheral hearing measures (puretone average, speech recognition threshold, and speech identification scores); Model 2 – Cognitive measures (N-back scores, visual and auditory Stroop interference); Model 3 – Auditory processing measures (gap detection threshold, temporal fine structure scores, SCAP); Model 4 –Perceptual learning ability (PLA); Model 5 – Rapid adaptation slopes. (Same for tables 6 – 8)

Table 4

Results of Hierarchical Regression Analysis for the Elderly Hearing Impaired (EHI) Group

Condition	**Model**	**R²**	**Adj. R²**	**F**	**p**	**ΔR²**
Plausible +3 dB SNR	1	0.116	-0.049	0.70	0.564	—
	2	0.351	-0.028	0.93	0.520	0.234
	3	0.495	-0.066	0.88	0.579	0.144
	4	0.876	0.706	5.15	0.014	0.381*
	5	0.938	0.831	8.77	0.004	0.061*
Plausible 0 dB SNR	1	0.009	-0.177	0.05	0.985	—
	2	0.174	-0.309	0.36	0.909	0.164
	3	0.224	-0.639	0.26	0.977	0.050
	4	0.818	0.568	3.27	0.050	0.595*
	5	0.818	0.507	2.63	0.104	0.000
Implausible +3 dB SNR	1	0.167	0.011	1.07	0.389	—
	2	0.457	0.140	1.44	0.275	0.290
	3	0.595	0.144	1.32	0.344	0.138
	4	0.650	0.168	1.35	0.343	0.055
	5	0.728	0.261	1.56	0.285	0.078
Implausible 0 dB SNR	1	0.297	0.165	2.25	0.121	—
	2	0.357	-0.018	0.95	0.504	0.060
	3	0.399	-0.269	0.60	0.783	0.042
	4	0.413	-0.394	0.51	0.850	0.014
	5	0.463	-0.457	0.50	0.859	0.050

Table 5. Results of Hierarchical Regression Analysis for the Elderly Hearing Aid (EHA) Group

Condition	**Model**	**R²**	**Adj. R²**	**F**	**p**	**ΔR²**
Plausible +3 dB SNR	1	0.011	-0.175	0.06	0.981	—
	2	0.216	-0.241	0.47	0.837	0.205
	3	0.372	-0.325	0.53	0.829	0.156
	4	0.584	0.011	1.02	0.503	0.211
	5	0.611	-0.056	0.92	0.574	0.027
Plausible 0 dB SNR	1	0.178	0.024	1.16	0.357	—
	2	0.494	0.199	1.68	0.206	0.316
	3	0.606	0.168	1.39	0.318	0.112
	4	0.681	0.242	1.55	0.272	0.075

	5	0.693	0.166	1.31	0.370	0.012
Implausible +3 dB SNR	1	0.054	-0.124	0.30	0.824	—
	2	0.099	-0.427	0.19	0.983	0.045
	3	0.265	-0.553	0.32	0.953	0.166
	4	0.305	-0.649	0.32	0.958	0.041
	5	0.314	-0.861	0.27	0.978	0.009
Implausible 0 dB SNR	1	0.071	-0.103	0.41	0.749	—
	2	0.221	-0.234	0.49	0.828	0.149
	3	0.349	-0.375	0.48	0.865	0.128
	4	0.775	0.466	2.50	0.011	0.426*
	5	0.787	0.422	2.16	0.157	0.012